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Research Article

Low-Frequency Noise Reduction by Earmuffs with Flax Fibre-Reinforced Polypropylene Ear Cups

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Soldiers and supporting engineers are frequently exposed to high low-frequency (<500 Hz) cabin noise in military vehicles. Despite the use of commercial hearing protection devices, the risk of auditory damage is still imminent because the devices may not be optimally customised for such applications. This study considers flax fibre-reinforced polypropylene (Flax-PP) as an alternative to the material selection for the ear cups of commercial earmuffs, which are typically made of acrylonitrile butadiene styrene (ABS). Different weaving configurations (woven and nonwoven) and various noise environments (pink noise, cabin booming noise, and firing noise) were considered to investigate the feasibility of the proposed composite earmuffs for low-frequency noise reduction. The remaining assembly components of the earmuff were kept consistent with those of a commercial earmuff, which served as a benchmark for results comparison. In contrast to the commercial earmuff, the composite earmuffs were shown to be better in mitigating low-frequency noise by up to 16.6 dB, while compromising midfrequency acoustical performance. Consequently, the proposed composite earmuffs may be an alternative for low-frequency noise reduction in vehicle cabins, at airports, and at construction sites involving heavy machineries.

1. Introduction

Soldiers and supporting engineers are commonly exposed to high cabin noise in military vehicles, which includes firing noise and/or cabin booming noise. The energy content in such noises generally falls in the low-frequency range (<500 Hz). Typically, automobile manufacturers apply several passive and/or active acoustical treatments for cabin noise control. However, the maximum acoustical performance of the treatments may not be achieved due to other design considerations [1]. In practice, the simplest approach is to highlight the importance of hearing protection to the soldiers and engineers on the correct procedures in wearing hearing protection devices, earplugs and earmuffs (or ear defenders).

Earplugs are generally preferred as they are easy to put on and do not cause as much discomfort as earmuffs. Furthermore, they are inexpensive and, in a way, dispensable. However, poor fitting of earplugs is still a problem observed among some employees [2, 3], consequently compromising noise attenuation. In a study by Toivonen et al. [2], they reported a drop in noise attenuation of up to 10 dB when the earplugs were poorly fitted into the ear canals. However, the drop might not be necessarily due to the lack of user knowledge but could also be due to incompatible ear canals. Nonetheless, earplugs are usually inadequate in typical military environments. As such, earmuffs are typically recommended. One key advantage is the nondependency of acoustical performance on one's ear canals. If properly worn, earmuffs can provide better noise attenuation than earplugs [4]. Commercially, a wide selection of earmuffs is available, catering for use in different noise environments. Some models are even proprietary to gain an advantage among the competitors. However, a risk of auditory damage is still imminent because commercial earmuffs may not be optimised for reducing cabin noise in military vehicles. Alternatively, the acoustical performance of earmuffs can also be improved by modifying several design parameters such as ear cups, cushions, inner foam lining, and headbands [5–8].

Recently, Augustine [9] proposed the use of synthetic fibre-reinforced polymer composite as the material of the ear cups. The physical design was based on existing commercial earmuffs used by the crew in military aircraft. In total, three types of fibre were considered (aramid, glass, and carbon). For impulse noise, aramid fibre was shown to yield the highest noise attenuation (up to 28 dB). The other two fibres fared poorer with noise attenuation of up to 20 dB, comparable to the existing earmuffs. In contrary, these findings appeared otherwise in a continuous noise environment where the existing earmuffs were shown to be superior. Despite efforts to maintain consistency in the study, some parameters remained inconsistent such as cushions and headbands. Furthermore, the drilled holes at the sides of each ear cup could have introduced sound leakage. Separately, Ahmadi et al. [10] considered differently by combining nanoclay with acrylonitrile butadiene styrene (ABS), a common thermoplastic material used for the ear cups of commercial earmuffs. Experimentally, its acoustical performance was compared against single- and double-cup commercial earmuffs. Remarkably, the proposed material achieved notable noise attenuation (up to 9 dB) between 250 Hz and 8 kHz as compared to the commercial single-cup earmuff. However, such acoustical performance in the low-frequency range is still not ideal for cabin noise control in military vehicles.

Besides synthetic fibres, natural fibres—such as flax, hemp, and jute—have also caught research attention due to several advantages. Some of these advantages include good mechanical properties [11–14], good damping properties [12, 13], lightweight [13, 15, 16], low cost [14, 16], biodegradable, and environmental-friendly [13, 14, 17]. From literature, it is prominent that earlier studies focused on the viability of natural fibres but not on the understanding of their acoustical properties. It is only recently when Yang and Li [18] investigated the sound absorption properties of several natural fibres by means of an impedance tube. In comparison to synthetic fibres, they showed that natural fibres could exhibit good sound absorption properties with flax fibre being the highest in terms of noise reduction coefficient (0.65), nearly two times higher than glass fibre. Later, Prabhakaran et al. [16] extended the work by demonstrating the damping characteristics of flax fibre-reinforced epoxy pertaining to sound and vibration. In comparison with glass fibre-reinforced epoxy, the sound absorption coefficient was shown to be higher at 100 Hz (up to 21%) and beyond 2 kHz (up to 25%), respectively. In terms of vibration damping, flax fibre-reinforced epoxy was shown to be superior (50% higher) as compared to glass fibre-reinforced epoxy. At this point, these studies established a consistency in the acoustical properties of flax fibre. Subsequently, Mamtaz et al. [19] highlighted the potential of natural fibres for noise control applications with a review of related studies albeit extensive further work is still necessary.

These studies served as the motivation of this work to consider flax fibre-reinforced polypropylene (Flax-PP) as an alternative to the material selection for the ear cups of earmuffs. Additionally, different configurations were considered (woven and nonwoven). The present study aims to understand the feasibility of composite earmuffs for cabin noise control in military vehicles where the crew's exposure to low-frequency noise is still a concern to date [1]. Consequently, the proposed composite earmuffs may be a potential alternative for low-frequency noise control applicable in vehicle cabins, at airports, and at construction sites involving heavy machineries. The next section elaborates the details on the materials and methods. In Section 3, the results are presented and discussed. In Section 4, the limitations of this study are discussed and avenues for future work are highlighted. In Section 5, a conclusion is provided based on the findings.

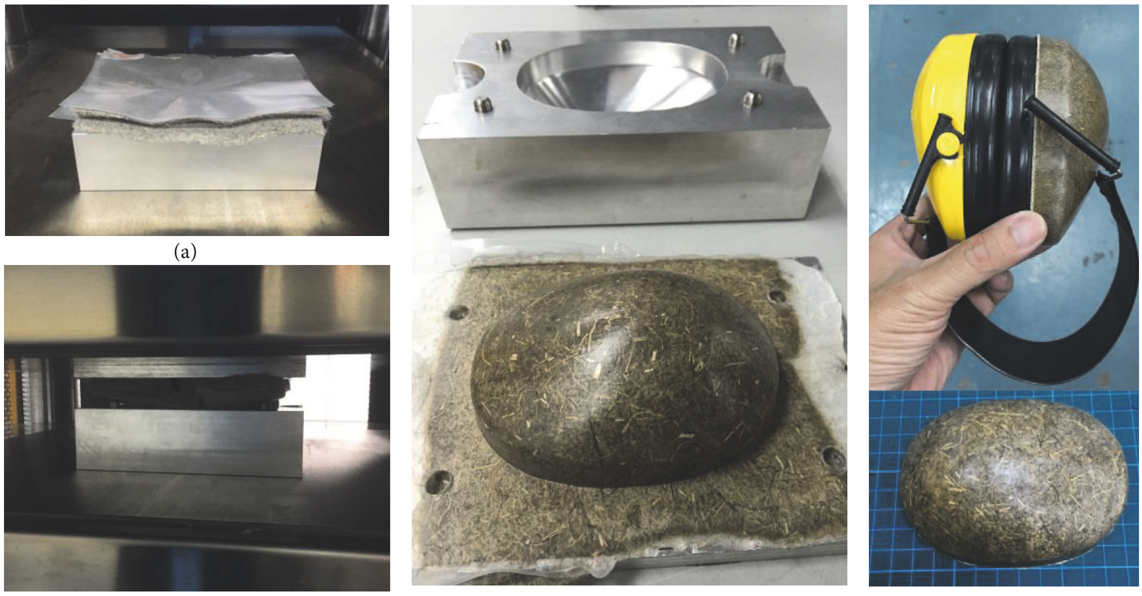
2. Materials and Methods

This section first presents the details of the commercial earmuff used for benchmarking and the different types of flax fabric considered for the fabrication of the composite ear cups. Subsequently, the fabrication process of the composite ear cups is presented. This section ends off with how the experiment was performed to obtain the acoustical performance of the commercial and the composite earmuffs.

2.1. Specimen Details and Materials. The composite ear cups were geometrically designed with high resemblance to the ear cups of a commercial earmuff (3 M™ Peltor™ Optime™ I H510F). The commercial earmuff served as the benchmark against the composite earmuffs. From the benchmarking, the acoustical benefits and drawbacks of the composite earmuffs would then be clearly identified. Hereinafter, for clarity and brevity, the commercial earmuff is referred to as the reference earmuff. Apart from the ear cups, the remaining components—inner foam lining, cushion, and headband—were kept identical to the reference earmuff. In other words, the composite earmuff shared the same assembly components as the reference earmuff except for the ear cups.

Three different types of flax fabric were considered in fabricating the composite ear cups. The flax fabrics included a nonwoven mat, a 2 × 2 twill weave mat, and a 4 × 4 hopsack weave mat. The nonwoven mat was provided by Eco-Technilin (Valliquerville, France), while the remaining mats were supplied by Composites Evolution (Derbyshire, England). For the polymer matrix, polypropylene films were used. These films were supplied by The Polyolefin Company (Singapore) in their unmodified grade (Cosmoplene Y101E). Table 1 shows the density of the respective flax fabrics and the polypropylene film.

The composite ear cups were manufactured using compression moulding technique in which the flax fabrics and polypropylene films were stacked in a prescribed sequence and placed between a two-piece aluminium mould as shown in Figures 1(a) and 1(b). The mould was designed to replicate the geometrical profile of the ear cups from the reference earmuff. Next, the setup was placed into the Collin hot press



(a) (b) (c) (d)

Figure 1: Manufacturing process of the composite ear cups: (a) a stack of flax fabrics and polypropylene films placed on top of one side of the two-piece aluminium mould; (b) hot press compression moulding; (c) unprocessed composite ear cup; (d) processed composite ear cup (bottom image) and assembled earmuff for experiment (top image).

Table 1: Density of the respective flax fabrics and the polypropylene film.

Fabric/film	Fabric density [g/m^2]
Nonwoven mat	300
2 × 2 twill weave mat	400
4 × 4 hopsack weave mat	500
Polypropylene film	90

Table 2: Fibre volume fraction and number of fibre layers in each composite ear cup.

Fabric	Number of fibre layers	Fibre volume fraction [%]
Nonwoven mat	4	27
2 × 2 twill weave mat	3	27
4 × 4 hopsack weave mat	3	33

(Figure 1(b)) for fabrication. The process lasted for 15 minutes with the processing temperature and the pressure loading maintained at 190°C and 20 bar, respectively. Subsequently, the setup was cooled to room temperature at a rate of −10°C per minute. The fabricated composite ear cup (Figure 1(c)) was then prepared by removing the asset materials and assembling them with the remaining components—inner foam lining, cushion, and headband—to form the earmuff as shown in Figure 1(d). Note that the fabrication process could only produce one composite ear cup at a time. Therefore, the fabrication process was repeated to obtain the required number of composite ear cups. Figure 2 provides a closed-up view of each composite ear cup assembled with the remaining components of the earmuff except the headband. Table 2 presents the fibre volume fraction and the number of layers in each composite ear cup.

2.2. Experimental Details. The experiment adhered to the guidelines in BS EN ISO 4869-3 [20] except for the use of a sound quality head and torso simulator (Brüel & Kjær Type 4100) as opposed to a cylindrical acoustic test fixture. Together with a data acquisition unit (Brüel & Kjær Type 3663), the simulator was placed on a standard test table at the centre of the reverberation room with a volume of 226.9 m^3. An omnidirectional loudspeaker (Larson Davis BAS001) was placed at one of the room corners to transmit pink noise (50–12,000 Hz), which was generated and amplified by a noise generator (Brüel & Kjær Type 1405) and a signal amplifier (Larson Davis BAS002), respectively. An additional microphone was positioned at 1 m away from each side of the simulator's ear to record the sound pressure level (SPL) during each measurement. The additional measurements served to ensure consistency in the reverberant sound field as that recorded by the simulator without any earmuff (open ear). As for subsequent stages of the experiment involving firing noise and cabin booming noise, the omnidirectional loudspeaker was substituted by a pair of active loudspeakers (Yamaha DXR15) due to technical limitations. Similarly, the loudspeakers were positioned at two of the room corners to transmit the respective audio signals—downloaded from the Internet—which were played via an audio system (Sony ZS-RS70BT).

It must be emphasised that the simulator was designed for evaluating sound quality in automobile cabins and other

(a) (b) (c)

Figure 2: Closed-up view of the composite ear cups assembled with the inner foam lining and cushion: (a) nonwoven; (b) 2 × 2 twill weave; (c) 4 × 4 hopsack weave.

optimisation studies [21]. Therefore, the presented results would only serve as relative measurements for benchmarking of the composite earmuffs with the reference earmuff. The same limitation was highlighted in a recent study by Ang et al. [22]. In this case, the presented results must not be misunderstood as a direct indication of real-ear attenuation values, which is one of the most accurate evaluation methods for hearing protection devices [23].

Despite the simulator's design to emulate the head and torso of a human as close as possible, leakage paths would still exist differently in both cases. Having this concern in mind, efforts were made to minimise experimental uncertainty, which could be caused by possible leakage paths that may exist in the simulator. Prior to the donning of each earmuff on the simulator, a visual inspection was performed to make sure that the moulded pinnae remained well-fitted in their allocated recesses. This inspection was necessary due to the likelihood that the process of removing the earmuff from the simulator could affect the fitting of the moulded pinnae. Experimental uncertainty was further minimised by maintaining consistency in the earmuff's position and fitting on the simulator. This consistency was achieved by noting the scales around the pinnae of the simulator and on top of its head, which could be partially seen in Figure 3(a). Lastly, discrepancy in headband force between each earmuff was minimised by maintaining the extended length of the headband. Note that, to measure the headband force, a specially designed test rig would be required as shown by Hsu et al. [24], for example. Such consideration would require expertise and was, therefore, beyond the scope of the present study.

Six measurements were recorded for each earmuff in each type of noise source. This number of measurements exceeded the recommendation of the test standard (at least three measurements). The purpose of exceeding the standard's recommendation was to reduce experimental uncertainty from the average of more datasets. The measurement duration was 30 s for pink noise and cabin booming noise, while the measurement duration was 10 s for firing noise. Additionally, the SPL of each noise source was ensured to be at least 15 dB higher than the background noise in the room. The measurements were then postprocessed and computed in terms of insertion loss (IL) as defined by the SPL difference between with and without the earmuff worn on the simulator, which is given by [25, 26]

$$\mathrm{IL}_f = L_{\mathrm{wo},f} - L_{\mathrm{w},f}, \quad (1)$$

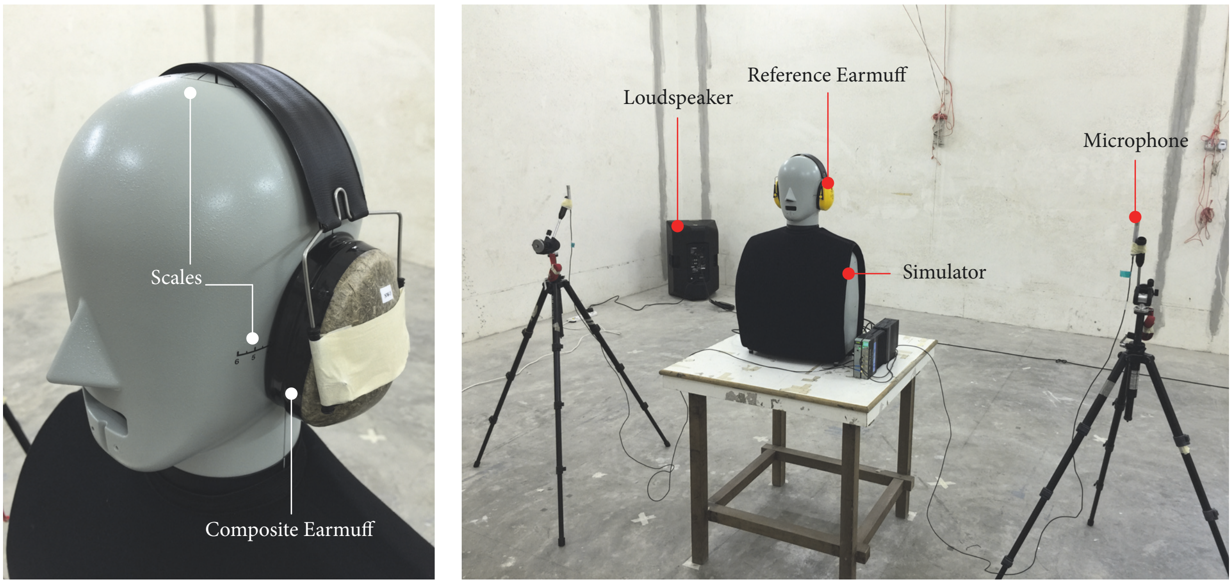
where the subscript f denotes a frequency-dependent term and L_{wo} and L_{w} denote the time-averaged SPL without and with the earmuff worn on the simulator, respectively. Based on the assumption of a diffuse field, both terms (L_{wo} and L_{w}) were taken as the average between the SPL at both ears of the simulator. Figure 3(b) shows an overview of the experimental setup in the reverberation room.

3. Results

This section presents and discusses the acoustical performance of the earmuffs in the respective noise sources. The results were plotted in narrowband frequency range rather than octave band frequency range, which should be the case in the context of evaluating hearing protection devices [23]. The intention was to better illustrate the overall characteristics of the composite earmuffs, which are crucial for future developmental studies to improve their acoustical performance. The IL curves are bounded by a shaded region, representing the upper and the lower limits of the expanded uncertainty at a confidence level of 95% (i.e., coverage factor = 2) [27]. Systematic error was taken to be 0.5 dB.

3.1. Acoustical Performance of the Composite Earmuffs in Pink Noise. The IL curve of each earmuff was first determined in pink noise. Figure 4(a) shows the typical spectrum of the pink noise generated in the reverberation room. To identify the acoustical benefits and drawbacks of the composite earmuffs, each IL curve was compared against that of the reference earmuff (Figures 4(b)–4(d)). However, a comparative study to determine the ideal composite earmuff was not presented due to differences in their composition.

In Figures 5(b)–5(d), the overall trend of the IL curves for each composite earmuff was the same despite the differences



(a) (b)

Figure 3: (a) Closed-up view of the simulator with the composite earmuff worn based on the scales; (b) overview of the experimental setup in the reverberation room with the reference earmuff worn on the simulator.

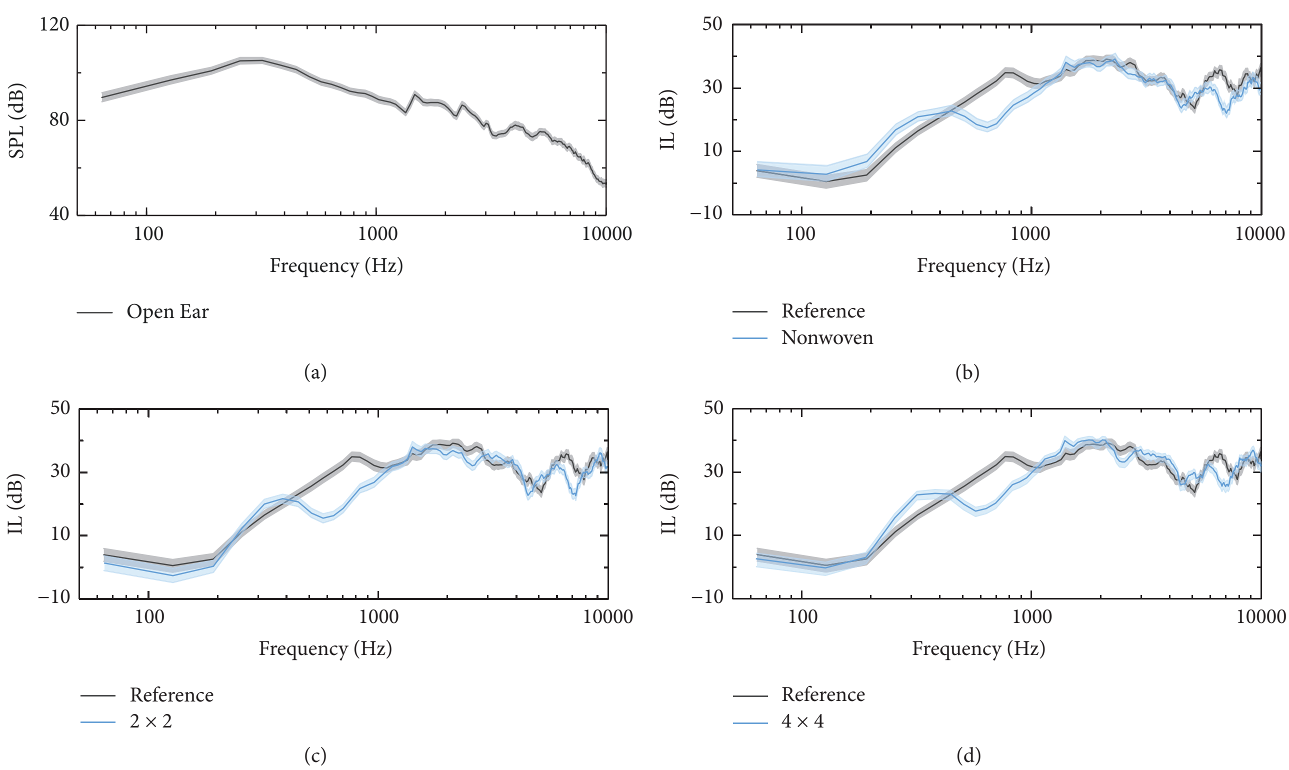


Figure 4: (a) Averaged sound pressure level of the pink noise in the reverberation room measured by the simulator without any earmuff (open ear); comparison between the insertion loss curve of (b) the reference and the nonwoven composite earmuffs; (c) the reference and the 2 × 2 twill weave composite earmuffs; and (d) the reference and the 4 × 4 hopsack weave composite earmuffs. Shaded area is bounded by the upper and the lower limits of the expanded uncertainty at a confidence level of 95%.

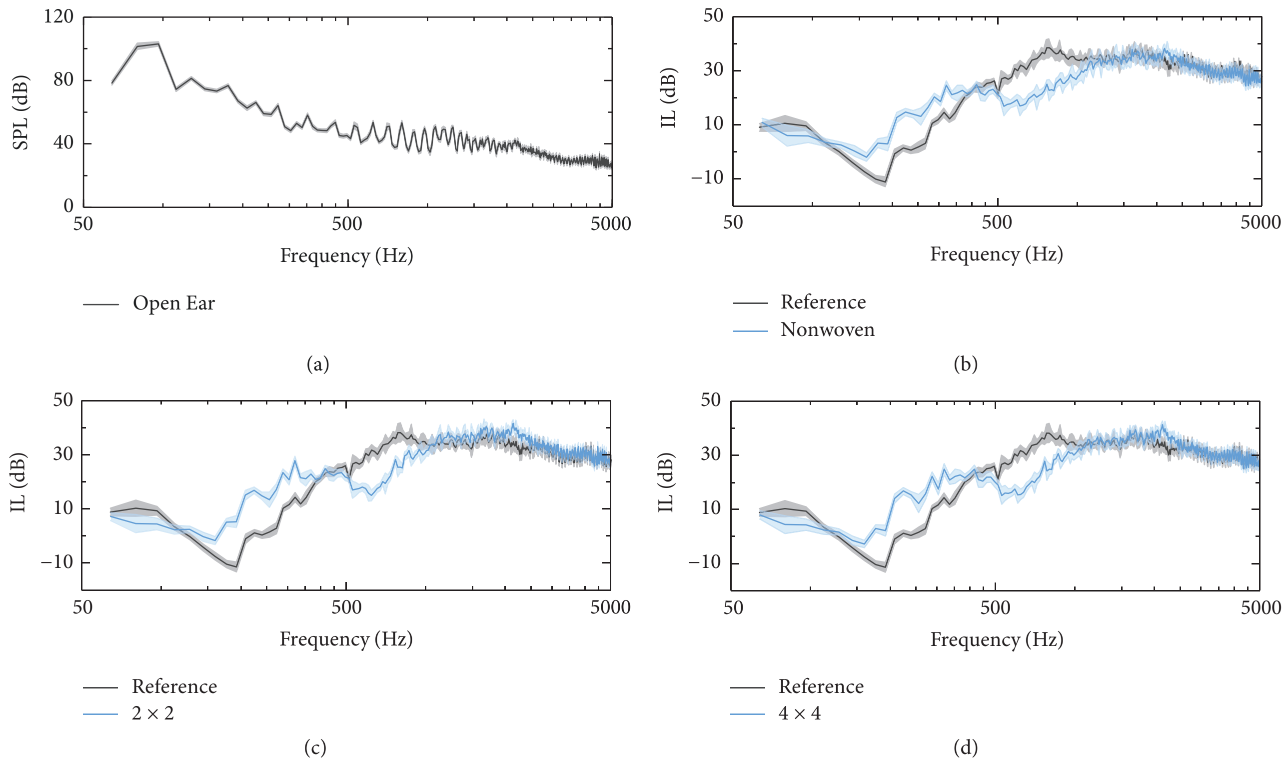


Figure 5: (a) Averaged sound pressure level of the cabin booming noise in the reverberation room measured by the simulator without any earmuff (open ear); comparison between the insertion loss curve of (b) the reference and the nonwoven composite earmuffs; (c) the reference and the 2 × 2 twill weave composite earmuffs; and (d) the reference and the 4 × 4 hopsack weave composite earmuffs. Shaded area is bounded by the upper and the lower limits of the expanded uncertainty at a confidence level of 95%.

in their composition. Between 100 and 200 Hz, an IL dip was consistently observed across the different earmuffs. Knowing that the physical geometries of the composite ear cups were kept identical to that of the reference earmuff, the cause of the IL dip would not be attributed to the assembly components of the earmuff. This understanding narrowed the list of possible causes of the IL dip to either the acoustic resonance of the enclosed air cavity or the pumping motion of the ear cups.

The former could be explained by considering the mathematical formulation to approximate acoustic resonance in an enclosed volume. Evidently, the air cavity enclosed by the ear cup would take the boundary profile of a highly irregular shape. However, Boyer et al. [28] and Paurobally and Pan [29] mentioned that the acoustic stiffness of the air cavity could be approximated by considering it as a hemicylindrical volume. In this case, the acoustic stiffness of the air cavity k_{air} is given by [28]

$$k_{\text{air}} = \frac{\rho c^2 S^2}{V}, \quad (2)$$

where ρ and c denote the density of and the sound speed in air, respectively, in the ear cup; S denotes the cross-sectional area of the cavity; and V denotes the volume of the cavity. Knowing that the acoustic resonance of the air cavity is inversely proportional to the square root of the acoustic stiffness, it could be deduced that the small volume of the air cavity would result in a high-frequency acoustic resonance. Referring to Figures 4(b)–4(d), the IL dip at around 4.5–5.1 kHz could be attributed to the cavity resonance. This deduction could be drawn from the understanding that the volume of the cavity in each type of ear cup would be nearly identical since their physical geometries were maintained consistent. Intuitively, the cavity resonance would occur at around the same frequency, which could be at around 4.5–5.1 kHz as mentioned earlier. This understanding could be further reinforced by Boyer et al. [6] where they found that cavity resonance generally occurs at high frequency, consistent across the tested earmuffs. In their case, the cavity resonance occurred at around 4.0–4.5 kHz.

Based on the above understanding, it is highly possible that the IL dip at around 100–200 Hz was attributed to the pumping motion of the ear cups, which is dependent on the design parameters and the leakages around the cushion pads [30]. Boyer et al. [6] revealed that the pumping motion of the ear cups would highly influence the acoustical performance of the earmuff at low frequency. Separately, Boyer et al. [28] mentioned that the pumping motion of the ear cups would typically occur at around 100–300 Hz. Hence, it could be inferred that the IL dip at around 100–200 Hz was attributed to the pumping motion of the ear cups. As mentioned earlier, the pumping motion of the ear cups is not only dependent on the design parameters, but also the leakages around the cushion pads. Typically, it is challenging to achieve a perfect seal due to a nonuniform curvature profile around the ears. To minimise such leakages, the headband force could be increased, applying more pressure on the temporal bone. For instance, Boyer et al. [28] demonstrated that a higher headband force would achieve a better sealing of the cushion pads, leading to an improved low-frequency IL of the earmuffs. However, the resulting high pressure would compromise comfort and might discourage the user from wearing the earmuff over an extended period of time [8].

In contrast to the reference earmuff, a higher IL was achieved in the low-frequency range (<450 Hz) by all composite earmuffs. This observation was more prominent for the 4×4 hopsack weave and the nonwoven earmuffs with an IL of up to 5.6 dB at 256 and 320 Hz, respectively. The 2×2 twill weave earmuff fared poorer with an IL of only up to 3.6 dB at 320 Hz. Thereafter, the IL of all composite earmuffs gradually decreased as the frequency approached the second IL dip at 640 Hz. This dip caused a drop in IL for the composite earmuffs between 510 and 1090 Hz. Conversely, the same observation was not made for the reference earmuff. Based on the similarity in occurrence of the IL dip observed for each composite earmuff, the second IL dip could be due to one of the structural resonances of the composite ear cups.

At the high-frequency range, more IL dips were observed for the composite earmuffs at 2560, 4480, and 7040 Hz. Keeping in mind the intention of this study, these dips are not as critical since conventional acoustical treatments in the vehicle cabins are likely sufficient to complement noise attenuation at such high frequencies [1]. Nonetheless, with such acoustical performance achieved by the composite earmuffs in the low-frequency range, it was of great interest to evaluate their practicality in vehicle cabins.

3.2. Acoustical Performance of the Composite Earmuffs in Cabin Booming Noise. Booming noise is an undesirable phenomenon within a vehicle cabin. Generally, most of the noise energy falls below 500 Hz as illustrated in Figure 5(a). Figures 5(b)–5(d) show the comparison of the IL curves between the reference earmuff and the respective composite earmuffs.

A similar global trend in IL was observed for all composite earmuffs, consistent with the findings from Section 3.1. Again, the first IL dip was observed for all earmuffs. However, for the composite earmuffs, only the second IL dip (640 Hz) was prominent. The absence of the other IL dips could be due to the inherent low acoustical energy of the cabin booming noise at high frequency (Figure 5(a)).

Likewise, better IL in the lower frequencies (128–416 Hz) was achieved by the composite earmuffs as opposed to the reference earmuff. In this frequency range, an IL of up to 16.6 dB was achieved by the 2×2 twill weave earmuff, while the other composite earmuffs fared slightly poorer by 1-2 dB. Again, the acoustical performance for all composite earmuffs beyond 450 Hz decreased progressively towards the second IL dip at 640 Hz, affecting unfavourably up to 1090 Hz. As such, a compromise in acoustical performance by up to 16.6 dB was observed for the 2×2 twill weave and the 4×4 hopsack weave earmuffs. Conversely, the nonwoven earmuff was marginally better by 1.5 dB.

At high frequencies (1985–2425 Hz), better IL of up to 6.8 dB was achieved albeit not as prominent for the nonwoven earmuff. Beyond this point, no noticeable differences in acoustical performance were observed for the composite earmuffs in contrast to the reference earmuff. Nonetheless, the significance of the acoustical performance exhibited by the composite earmuffs in the mid- and high frequencies may not be crucial in low-frequency noise control applications.

3.3. Acoustical Performance of the Composite Earmuffs in Firing Noise. The frequency content of firing noise in vehicle cabins is similar to cabin booming noise where most of the noise energy falls below 500 Hz as illustrated in Figure 6(a). Figures 6(b)–6(d) show the comparison of the IL curves between the reference earmuff and the respective composite earmuffs.

The overall trend of the IL curves was again similarly observed for the composite earmuffs including the second IL dip. However, the range of improved acoustical performance in the low-frequencies was observed to be slightly narrower (160–360 Hz) as opposed to the earlier findings in Sections 3.1 and 3.2. Nonetheless, decent IL of 9.8–10.3 dB was still achieved, particularly at 208 Hz, by the composite earmuffs.

The second IL dip was observed to be less distinct with a wider bandwidth ranging from 560 to 720 Hz. Despite this dip, the compromise in acoustical performance in the midfrequencies (400–1008 Hz) remained comparable in bandwidth as opposed to the earlier findings in Sections 3.1 and 3.2. However, a minor downward shift in frequency was observed. The 2×2 twill weave and the 4×4 hopsack weave earmuffs were shown to reach a maximum drop in IL at 608 Hz of 14.3 dB and 12.4 dB, respectively. As for the nonwoven earmuff, the maximum drop in IL is 11.6 dB at 736 Hz. Beyond 1008 Hz, no noticeable differences in acoustical performance were observed for the composite earmuffs in contrast to the reference earmuff.

4. Discussion

The findings of this present study were based on solely experimental work. Analytical models could be used to predict the IL curves of each earmuff as a form of validation. Generally, analytical models are developed based on the concepts of lumped parameters modelling. Boyer et al. [28], for instance, provided a comprehensive review in this aspect. In their review, they stated that analytical models would only provide an approximation of the acoustical performance for a given earmuff up to about 1 kHz and before the occurrence of the first acoustic or structural resonance. Considering typical environmental noises, it is essential to understand the acoustical performance of the earmuff above 1 kHz. In this case, the limitation could be addressed by numerical methods such as finite element method or boundary element method.

Numerical methods are generally suitable to approximate the acoustical performance of earmuffs up to about 5 kHz [28] where the limitations now lie on the mesh density of the model and the computational resources required

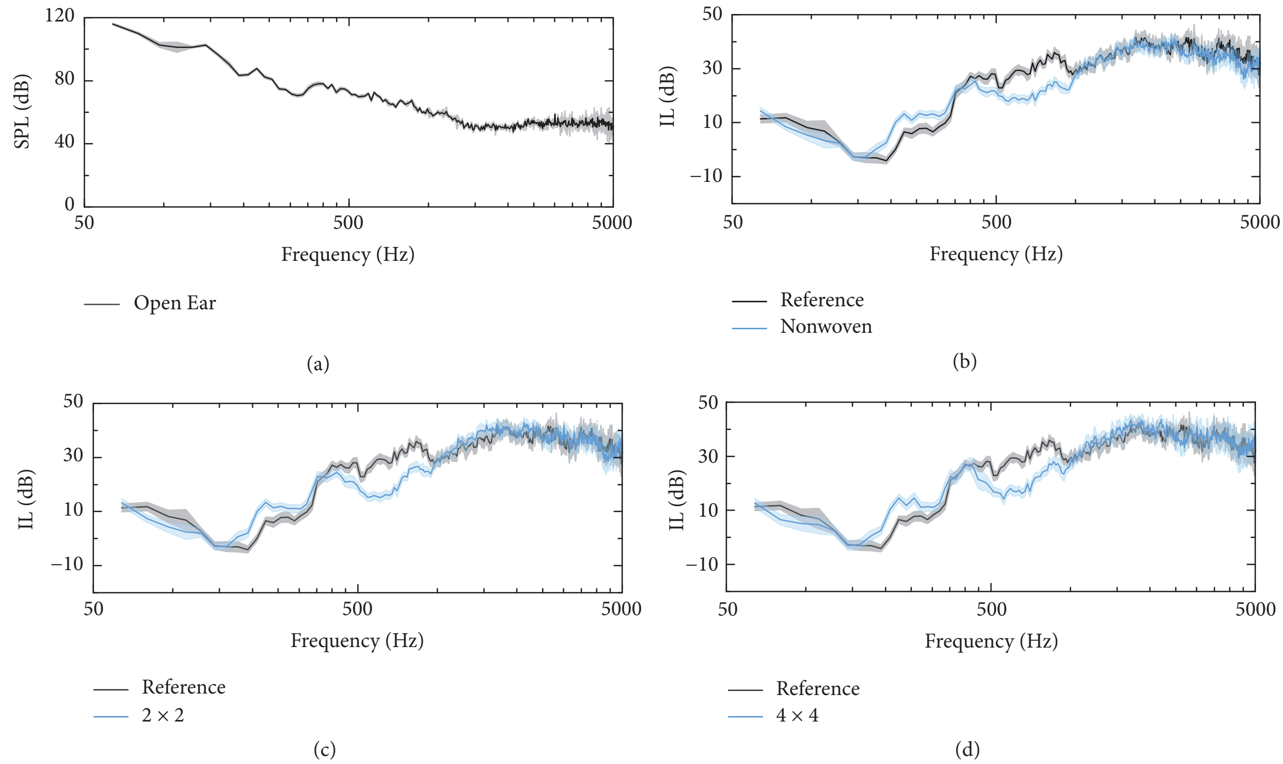


Figure 6: (a) Averaged sound pressure level of the firing noise in the reverberation room measured by the simulator without any earmuff (open ear); comparison between the insertion loss curve of (b) the reference and the nonwoven composite earmuffs; (c) the reference and the 2 × 2 twill weave composite earmuffs; and (d) the reference and the 4 × 4 hopsack weave composite earmuffs. Shaded area is bounded by the upper and the lower limits of the expanded uncertainty at a confidence level of 95%.

for high-frequency prediction. Although numerical methods could address the limitation of analytical models, challenges remain—to date—where the material properties and the interaction between each component of the earmuff must be correctly specified. Else, erroneous results would be expected. This statement could be supported by the literature where researchers have attempted to develop a robust numerical model to approximate—with high accuracy—the noise attenuation of a given earmuff [28, 31, 32]. As demonstrated by Boyer et al. [28], rigorous experiments would be necessary to obtain important parameters such as the headband force and the cushion dynamic stiffness. Recently, researchers have attempted to increase the complexity of the numerical model by considering the influence of the human skin, ear canal, cartilage, and bone [33, 34]. Evidently, the increase in modelling complexity would result in the need for higher computational resources as pointed out by Sgard et al. [33]. However, despite the high complexity of the numerical model, large discrepancies between the measurement and the simulation were still observed [28].

In the present study, the composite ear cups would inevitably increase the complexity of the numerical model considering that the material of the ear cup is no longer homogeneous or isotropic in contrast to ABS. As such, the present study provides an avenue for future work to develop the numerical model of the composite ear cups to predict the respective IL curves, not to mention that the effort required could lead to a thesis by itself [35]. Consequently, with a robust and accurate model, parametric study can be performed to optimise the design of the ear cups for enhanced acoustical performance.

5. Conclusions

In conclusion, this study proposed the potential of improving low-frequency noise reduction of commercial earmuffs by considering Flax-PP as an alternative to the material selection for the ear cups. The material, however, involved a trade-off in acoustical performance at the midfrequencies (510–1090 Hz) in contrast to a reference earmuff. Three different types of flax fabrics were considered (nonwoven mat, 2 × 2 twill weave, and 4 × 4 hopsack weave). Due to the differences in their composition, a comparative study to determine the ideal composite earmuff was not considered.

For practicality, the potential of the composite earmuffs was demonstrated by evaluating their acoustical performance under two types of cabin noise encountered in military vehicles (booming noise and firing noise). Results showed an improvement in IL by up to 16.6 dB within the range of 128–416 Hz in booming noise and up to 10.3 dB within the range of 160–360 Hz in firing noise. Future work to optimise the composition and physical design of the composite ear cups is imperative to improve their acoustical performance and possibly reduce the compromise at the midfrequencies.

Consequently, the proposed composite earmuffs may be a potential alternative for low-frequency noise reduction applicable in vehicle cabins, at airports, and at construction sites involving heavy machineries.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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